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Abstract

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Abstract

- Deutsch -

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Versuche in das Abstract folgende Punkte aufzunehmen: Fragestellung der Arbeit, methodische Vorgehensweise oder die Hauptergebnisse deiner Arbeit.

Inhaltsverzeichnis

List of abbreviations

DE	Differential Equation
DFT	Discrete Fourier Transform
FEM	Finite Element Method
FT	Fourier Transform
FFT	Fast Fourier Transform
IDFT	Inverse Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
LS	Least Squares
ODE	Ordinary Differential Equation
PDE	Partial Differential Equation

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1. Fundamentals

1.1. Heat Equation

The conduction of heat within a medium can be described using the following partial differential equation (PDE):

$$\frac{\partial u}{\partial t} = \alpha \nabla^2 u \tag{1.1}$$

With u being a function of space and time and α being a positive constant. For this paper u will be defined in terms of one spacial dimension:

$$u := u(x,t) \tag{1.2}$$

$$\frac{\partial u}{\partial t} = \alpha \frac{\partial^2 u}{\partial x^2} \tag{1.3}$$

$$x \in \chi \subset \mathbb{R} \quad t \in \tau \subset \mathbb{R} \tag{1.4}$$

$$x_0 \leq x \leq x_n \quad t_0 \leq t \leq t_n \tag{1.5}$$

[1]
In order to not only model the conduction of heat within a medium but also a heating process, a new function $h : \chi \times \tau \to \mathbb{R}$ is introduced:

$$\frac{\partial u}{\partial t} = \alpha \frac{\partial^2 u}{\partial x^2} + h(x,t) \tag{1.6}$$

For this paper it is assumed that initial and boundary values are known:

$$a, b \in \mathbb{R} \tag{1.7}$$

$$f : \chi \to \mathbb{R} \tag{1.8}$$

$$u(x_0, t) = a \quad u(x_n, t) = b \tag{1.9}$$

$$u(x, t_0) = f(x) \tag{1.10}$$

Applying the Fourier transform (FT) w.r.t x to 1.6 yields the inhomogeneous ordinary differential equation (ODE):

$$\hat{u} = \mathfrak{F}(u) \quad \hat{h} = \mathfrak{F}(h) \tag{1.11}$$

$$\frac{d}{dt}\hat{u} = -\alpha\omega^2\hat{u} + \hat{h} \tag{1.12}$$

A solution to 1.12 is given by:

$$\hat{u} = \hat{u}_0 + \hat{u}_p \tag{1.13}$$

Where $\hat{u}_0$ is the homogeneous solution and $\hat{u}_p$ is the particular integral. In order to solve this ODE for the particular integral $\hat{h}$ has to be known. [2] The choice of h is, except to some restrictions, arbitrary. Therefore an approximate solution to 1.12 $\hat{u}_a$ is obtained by the forward euler scheme:

$$\frac{d}{dt}\hat{u} \approx \frac{\Delta\hat{u}}{\Delta t} \tag{1.14}$$

$$\hat{u}_{t+1} = \hat{u}_t + \Delta t(-\alpha\omega^2\hat{u} + \hat{h}) \tag{1.15}$$

$$\hat{u}_a = [\hat{u}_{t_0}, ..., \hat{u}_{t_n}] \tag{1.16}$$

In order to apply the euler scheme successfully an initial condition $\hat{u}_0$ has to be known. This initial condition is obtained by applying the discrete Fourier transform (DFT) to an initial temperature distribution along x:

$$\hat{u}_0 = \mathfrak{F}(f(x)) \tag{1.17}$$

[3]
The forward euler scheme is used here because it is fairly easy to implement. By applying the inverse discrete Fourier transform (IDFT) to $\hat{u}_a$ an approximate solution to 1.6 can be obtained. To decrease computing time, the fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT) is used instead of the DFT and IDFT.

1.2. Finite Element Method

The finite element method (FEM) is a method to approximate solutions for differential equations (DE) within a certain domain Ω. This is done by discretizing the spacial domain. Assume that a DE is given by:

$$m, n \in \mathbb{N} \quad \zeta \in \Omega \subset \mathbb{R} \quad m \geq 1 \tag{1.18}$$

$$\frac{\partial^m y}{\partial \zeta^m} - g(y) = r(\zeta, t) \tag{1.19}$$

It is assumed that g is a linear function that can also contain partial derivatives of y w.r.t. time, y takes the value 0 at the boundary Γ and $y(\zeta, 0) = f(\zeta)$. An approximate solution to y is given by μ, which is expressed as a sum of basis functions contained in the set ϕ:

$$\mu(\zeta, t) = \sum_{j=1}^{N} c_j(t)\phi_j(\zeta) \tag{1.20}$$

The residual is defined as:

$$\mathfrak{r} = \frac{\partial^m \mu}{\partial \zeta^m} - g(\mu) - r(\zeta, t) \tag{1.21}$$

Furthermore the residual is required to be orthogonal to all basis functions:

$$\langle \mathfrak{r}, \phi_k \rangle = 0 \quad \forall \phi_k \in \phi \tag{1.22}$$

Since the functions in ϕ are known, it is only required to find the coefficients $c_j(t)$ in 1.20. To find those coefficients 1.22 needs to be expressed as follows:

$$\int_\Omega \frac{\partial^m \mu}{\partial \zeta^m}\phi_k \, d\zeta - \int_\Omega g(\mu)\phi_k \, d\zeta = \int_\Omega r(\zeta, t)\phi_k \, d\zeta \quad \forall \phi_k \in \phi \tag{1.23}$$

If μ is substituted with 1.20 the following is obtained:

$$\sum_{j=1}^{N}((\int_\Omega \frac{\partial^m \phi_j}{\partial \zeta^m}\phi_k \, d\zeta)c_j(t) - g((\int_\Omega \phi_k \phi_j d\zeta)c_j(t))) = \int_\Omega r(\zeta, t)\phi_k \, d\zeta \quad \forall \phi_k \in \phi \tag{1.24}$$

It is also necessary to apply divergence theorem to the first integral term taking into account that y at Γ is 0. Since ζ is one dimensional, the divergence theorem becomes integration by parts:

$$\int_\Omega \frac{\partial^m \phi_j}{\partial \zeta^m}\phi_k \, d\zeta = -\int_\Omega \frac{\partial^{m-1} \phi_j}{\partial \zeta^{m-1}} \frac{\partial \phi_k}{\partial \zeta} \, d\zeta \quad \forall \phi_k \in \phi \tag{1.25}$$

Combining 1.24 and 1.25 yields:

$$-\sum_{j=1}^{N}((\int_{\Omega}\frac{\partial^{m-1}\phi_j}{\partial\zeta^{m-1}}\frac{\partial\phi_k}{\partial\zeta}\,d\zeta)c_j(t)+g((\int_{\Omega}\phi_k\phi_j d\zeta)c_j(t)))=\int_{\Omega}r(\zeta,t)\phi_k\,d\zeta\quad\forall\phi_k\in\phi \tag{1.26}$$

This formulation leads to a system of ODEs or a system of linear equations that can be solved either analytically or numerically. This formulation of FEM can be applied to 1.6:

$$\Omega=\chi\quad\Gamma=\{x_0,x_n\} \tag{1.27}$$

$$y(\zeta,t)=-u(x,t)\quad g(u)=-\frac{1}{\alpha}\frac{\partial u}{\partial t} \tag{1.28}$$

$$m=2\quad r(\zeta,t)=\frac{1}{\alpha}h(x,t) \tag{1.29}$$

$$u(x,0)=f(x)\quad u(x_0,t)=0\quad u(x_n,t)=0 \tag{1.30}$$

The set of basis functions is defined as a set of piecewise linear functions with constant step size Δx:

$$\phi_j(x)=\begin{cases}(x-x_{j-1})/\Delta x), & x_{j-1}\le x<x_j\\ (x_{j+1}-x)/\Delta x), & x_j\le x<x_{j+1}\\ 0, & \text{otherwise}\end{cases} \tag{1.31}$$

[4]
The stepsize Δx is defined by $\Delta x=\frac{x_n-x_0}{n-1}$. This results in the following system of ODEs:

$$\sum_{j=1}^{N}(\int_{\chi}\phi_j\phi_k dx)\frac{dc_j}{dt}=\alpha\sum_{j=1}^{N}(-\int_{\chi}\frac{d\phi_j}{dx}\frac{d\phi_j}{dx}dx)c_j(t)+\int_{\chi}h(x,t)\phi_k dx\quad\forall\phi_k\in\phi \tag{1.32}$$

Using matrix notation this becomes:

$$M^{N\times N},K^{N\times N} \tag{1.33}$$

$$M\dot{c}=Kc+d \tag{1.34}$$

The matrices M and K can be easily computed (Appendix A.1):

$$m_{ij}=\begin{cases}\frac{2\Delta x}{3}, & k=j\\ \frac{\Delta x}{6}, & |k-j|=1\\ 0, & otherwise\end{cases}\qquad k_{ij}=\begin{cases}\frac{-2\alpha}{\Delta x}, & k=j\\ \frac{\alpha}{\Delta x}, & |k-j|=1\\ 0, otherwise\end{cases} \tag{1.35}$$

However it is necessary to approximate d for each point in time using numerical integration schemes. Furthermore to solve this system of ODEs numerically an initial condition c_0 has to be known. [3]

It can be obtained using a least squares (LS) approach:

$$\sum_{j=1}^{N} \langle \phi_j, \phi_k \rangle c_j(0) = \langle f, \phi_k \rangle \quad \forall \phi_k \in \phi \tag{1.36}$$

$$Mc_0 = F \tag{1.37}$$

$$c_0 = M^{-1} F \tag{1.38}$$

[5]
Observe that by multiplying 1.34 with M^{-1} (A.2) yields a system of ODEs:

$$\dot{c} = M^{-1} K c + M^{-1} d \tag{1.39}$$

This system of ODEs can be solved using an euler scheme:

$$c_{t+1} = \Delta t M^{-1}(Kc + d) + c_t \tag{1.40}$$

Keep in mind that vector d is time dependent and has to be recomputed for each time step. To force the boudary condition $u(x,t) = 0 \; x \in \Gamma$ the first and last entry of any c_t has to be zero:

$$c_t^1 = 0 \quad c_t^n = 0 \quad \forall t \tag{1.41}$$

Therefore the Matrix M^{-1} has to be adjusted:

$$0 = \Delta t m(Kc + d) \tag{1.42}$$

$$\Rightarrow m = [0, 0, 0, \ldots, 0] \tag{1.43}$$

Here m is the first row vector of M^{-1} or the last one respectively [3]. Using 1.20 and the computed coefficients c the function $u(x,t)$ can be approximated. However this is equivalent to linear interpolation between c_n and c_{n+1} (Appendix A.3).

2. Implementation

The implementation of the discussed methods for solving the heat equation and for model order reduction was done in Matlab. Matlab was chosen as the programming language because it natively features matrix multiplication which finds heavy use in the previously mentioned methods. The second reason for this selection is that there exist ToolBoxes that already implement certain model order reduction methods.

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A. Appendix

A.1. Deriving matrices for FEM using piecewise linear functions

The so called triangle function is defined as follows:

$$\phi_j(x) = \begin{cases} (x - x_{j-1})/\Delta x), & x_{j-1} \leq x < x_j \\ (x_{j+1} - x)/\Delta x), & x_j \leq x < x_{j+1} \\ 0, \quad \text{otherwise} \end{cases} \tag{A.1}$$

[4] The following integrals have to be evaluated:

$$\int_\chi \phi_j \phi_k dx \quad \forall \phi_k \in \phi \tag{A.2}$$

$$-\int_\chi \frac{d\phi_j}{dx}\frac{d\phi_k}{dx} dx \quad \forall \phi_k \in \phi \tag{A.3}$$

With $\chi \subset \mathbb{R}$. Note that the product of two functions ϕ_j and ϕ_k and their derivatives is only under two conditions not zero:

1. $k = j$

Considering this case the integral A.2 becomes:

$$\int_{x_{j-1}}^{x_j} \phi_j^2 dx + \int_{x_j}^{x_{j+1}} \phi_j^2 dx \tag{A.4}$$

Because of symmetry only one of the above integrals have to computed:

$$2\int_{x_{j-1}}^{x_j} \phi_j^2 dx \tag{A.5}$$

$$= \frac{2}{\Delta x^2}\int_{x_{j-1}}^{x_j} (x - x_{j-1})^2 dx \tag{A.6}$$

$$\frac{2}{3\Delta x^2}\left[(x - x_{j-1})^3\right]_{x_{j-1}}^{x_j} = \frac{2}{3\Delta x^2}\Delta x^3 = \frac{2}{3}\Delta x \tag{A.7}$$

Integral A.3 for $i = j$ taking symmetry into account becomes:

$$-\int_{x_{j-1}}^{x_{j+1}} (\frac{d\phi_j}{dx})^2 dx = -\frac{1}{\Delta x^2} \int_{x_{j-1}}^{x_{j+1}} 1dx \tag{A.8}$$

$$= -\frac{1}{\Delta x^2} [x]_{x_{j-1}}^{x_{j+1}} = -\frac{2}{\Delta x} \tag{A.9}$$

2. $|j - k| = 1$ A.2 becomes:

$$\frac{1}{\Delta x^2} \int_{x_j}^{x_{j+1}} (x - x_j)(x_{j+1} - x) dx \tag{A.10}$$

$$= \left[\frac{1}{2} x^2 x_{j+1} - \frac{1}{3} x^3 - x x_{j+1} x_j + \frac{1}{2} x^2 x_j\right]_{x_j}^{x_{x_j+1}} = \frac{1}{6\Delta x^2} \Delta x^3 = \frac{1}{6} \Delta x \tag{A.11}$$

Finally A.3 has to be evaluated for this condition:

$$-\int_{x_j}^{x_{j+1}} \frac{d\phi_j}{dx} \frac{d\phi_{j+1}}{dx} dx = \frac{1}{\Delta x^2} \int_{x_j}^{x_{j+1}} 1dx = \frac{1}{\Delta x^2} [x]_{x_j}^{x_{j+1}} = \frac{1}{\Delta x} \tag{A.12}$$

A.2. Proof that matrix M is invertible

Let M_n be a matrix with $M_n \in \mathbb{R}^{n \times n}$ given by:

$$m_{ij} = \begin{cases} a, & k = j \\ b, & |k - j| = 1 \\ 0, & otherwise \end{cases} \tag{A.13}$$

It's determinant is given by the Laplace expansion:

$$det(M_n) = \sum_{j=1}^{n} (-1)^{i+j} a_{ij} N_{ij} \quad \forall i \tag{A.14}$$

N_{ij} is the determinant of the matrix M' that is obtained by removing the i^{th} row and j^{th} column of M_n. This expression can be simplified using the definition of m_{ij}:

$$det(M_n) = aN_{11} - bN_{12} \tag{A.15}$$

N_{11} is equivalent to $det(M_{n-1})$, since the indices of rows and columns of M' are in consecutive order and M' is a $n - 1 \times n - 1$ matrix :

$$N_{11} = det(M') \tag{A.16}$$

$$M' = \begin{bmatrix} m_{22} & \dots & m_{2n} \\ \vdots & \ddots & \vdots \\ m_{n2} & \dots & m_{nn} \end{bmatrix} \tag{A.17}$$

N_{12} can be obtained by calculating the determinant of M' using the Laplace expansion:

$$M' = \begin{bmatrix} m_{21} & m_{23} & \dots & m_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n3} & \dots & m_{nn} \end{bmatrix} \tag{A.18}$$

$$det(M') = m_{21} \cdot det(M'') \tag{A.19}$$

$$M'' = \begin{bmatrix} m_{33} & \dots & m_{3n} \\ \vdots & \ddots & \vdots \\ m_{n3} & \dots & m_{nn} \end{bmatrix} \tag{A.20}$$

In A.19 only the stated term has to evaluated since all entries of the first column of the second submatrix are zero. Therefore the determinant is zero. The row and column indices of M'' are in consecutive order and it is a $n-2 \times n-2$ matrix. Therefore M'' is equivalent to M_{n-2}. A.15 becomes:

$$det(M_n) = a \cdot det(M_{n-1}) - b^2 \cdot det(M_{n-2}) \tag{A.21}$$

Furthermore this implies $det(M_0) = 1$:

$$det(M_2) = a^2 - b^2 = a \cdot det(M_1) - b^2 \cdot 1 \tag{A.22}$$

$$\Rightarrow det(M_0) = 1 \tag{A.23}$$

Using the definition of 1.35 and 1.2 this can be seen as the following sequence:

$$a_0 = 1,\ a_1 = \frac{2\Delta x}{3} \tag{A.24}$$

$$a_{n+1} = \frac{2\Delta x}{3} \cdot a_n - \frac{\Delta x^2}{36} \cdot a_{n-1} \tag{A.25}$$

As described here [6] a recursive sequence converges if it is monotone and has a limit. A proof by induction shows that this sequence is monotone for $n \geq 1$.

Base case:

$$a_2 = (\frac{2\Delta x}{3})^2 - \frac{\Delta x^2}{36} = \Delta x^2(\frac{4}{9} - \frac{1}{36}) < \frac{2\Delta x}{3} = a_1 \tag{A.26}$$

Induction step: Assuming that $a_k < a_{k-1}$ holds, $a_{k+1} < a_k$ also holds:

$$a_{k+1} = \frac{2\Delta x}{3} \cdot a_k - \frac{\Delta x^2}{36} \cdot a_{k-1} < \frac{2\Delta x}{3} \cdot a_{k-1} - \frac{\Delta x^2}{36} \cdot a_{k-2} = a_k \tag{A.27}$$

The limit of this sequence is as follow:

$$\alpha = \lim_{n\to\infty} a_{n+1} = \lim_{n\to\infty} \Delta x \cdot \frac{2}{3} \cdot \lim_{n\to\infty} a_n - \lim_{n\to\infty} \Delta x^2 \cdot \frac{1}{36} \cdot \lim_{n\to\infty} a_{n-1} = 0 \cdot \alpha - 0 \cdot \alpha = 0 \tag{A.28}$$

Since this series is monotone and converges to zero as n goes to infinity, there is no $n \in \mathbb{N}$ for which $a_n = 0$. Therefore the determinant of the matrix M defined in 1.35 is not zero and M is invertible.

A.3. Equivalence of picewise linear polynomials and linear interpolation

A picewise linear polynomial in the form of:

$$u(x,t) = \sum_{j=1}^{N} c_j(t)\phi_j(x) \tag{A.29}$$

With ϕ_j being defined as A.1 and $c_j : \mathbb{R} \to \mathbb{R}$ is equivalent to linear interpolation with respect to x:

$$\hat{u}(x,t) = u_j + \frac{(u_{j+1} - u_j)(x - x_j)}{x_{j+1} - x_j} \tag{A.30}$$

for $x_j < x < x_{j+1}$ [7]. This can be shown by evaluating $u(x,t)$ between two neigbouring ϕ and $x_j < x < x_{j+1}$:

$$\begin{aligned}
u(x,t) &= \phi_j(x)c_j(t) + \phi_{j+1}(x)c_{j+1}(t) && \text{(A.31)}\\
&= \frac{x_{j+1} - x}{\Delta x}c_j(t) + \frac{x - x_j}{\Delta x}c_{j+1}(t) && \text{(A.32)}\\
&= \frac{x_{j+1} - x}{\Delta x}u_j + \frac{x - x_j}{\Delta x}u_{j+1} && \text{(A.33)}\\
&= \frac{(x_{j+1}u_j - xu_j) + (xu_{j+1} - x_ju_{j+1})}{\Delta x} && \text{(A.34)}\\
&= \frac{(u_{j+1} - u_j)x + x_{j+1}u_j - x_ju_{j+1}}{\Delta x} && \text{(A.35)}\\
&= \frac{(u_{j+1} - u_j)x + x_ju_j + \Delta x u_j - x_ju_{j+1}}{\Delta x} && \text{(A.36)}\\
&= u_j + \frac{(u_{j+1} - u_j)x - x_j(u_{j+1} - u_j)}{\Delta x} && \text{(A.37)}\\
&= u_j + \frac{(u_{j+1} - u_j)(x - x_j)}{x_{j+1} - x_j} && \text{(A.38)}
\end{aligned}$$